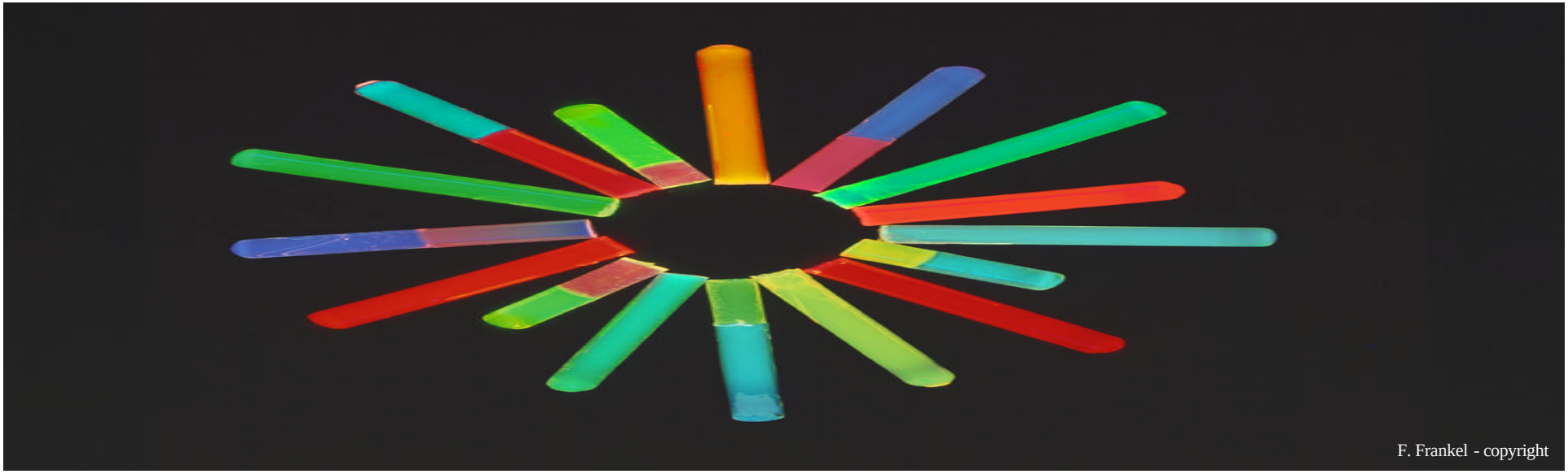

The Future of the National Nanotechnology Initiative

Dr. M.C. Roco

Chair, Subcommittee on Nanoscience, Engineering and Technology (NSET),
National Science and Technology Council (NSTC)

Senior Advisor for Nanotechnology, National Science Foundation

Boston, November 7, 2003

Report Documentation Page

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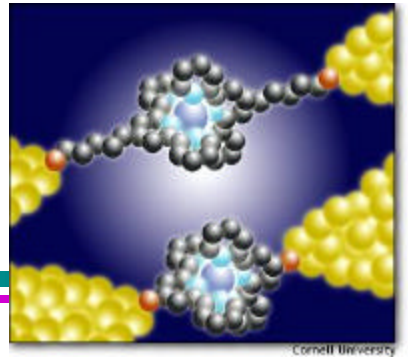
Nanotechnology

Definition on http://nano.gov/omb_nifty50.htm (2000)



- Working at the atomic, molecular and supramolecular levels, in the length scale of approximately 1 – 100 nm range, in order to understand and create materials, devices and systems with fundamentally new properties and functions because of their small structure

- **NNI definition encourages new contributions that were not possible before.**

  - novel phenomena, properties and functions at nanoscale, which are nonscalable outside of the nm domain

  - the ability to measure / control / manipulate matter at the nanoscale in order to change those properties and functions

  - integration along length scales, and fields of application

Broad societal implications

(examples of societal implications;
worldwide estimations made in 2000, NSF)

- **Knowledge base**: better comprehension of nature, life

- **New technologies and products: ~ $1 trillion/year by 2015**
  (With input from industry US, Japan, Europe 1997-2000, access to leading experts)

  Materials beyond chemistry: $340B/y
  Pharmaceuticals: $180 B/y
  Aerospace about $70B/y
  Electronics: over $300B/y
  Chemicals (catalysts): $100B/y
  Tools ~ $22 B/y

  Est. in 2000 (NSF) : about $40B for catalysts, GMR, materials, etc.; + 25%/yr
  Est. in 2002 (DB) : about $116B for materials, pharmaceuticals and chemicals

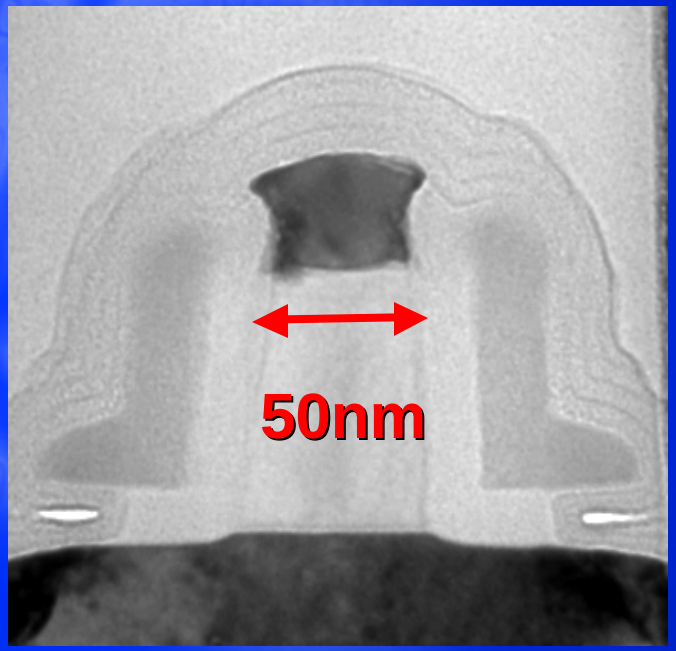
  Would require worldwide ~ 2 million nanotech workers

- **Improved healthcare**: extend life-span, its quality, physical capabilities

- **Sustainability**: agriculture, food, water, energy, materials, environment; ex: lighting energy reduction ~ 10% or **$100B/y**

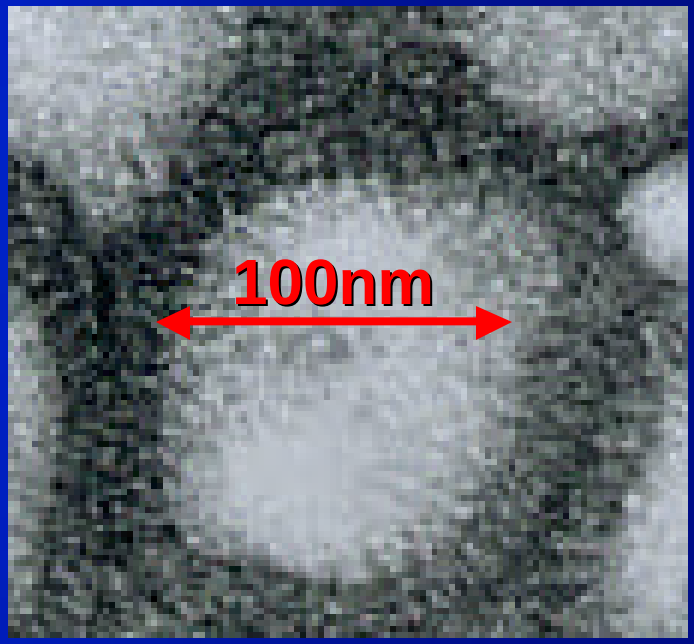
Example of today's technology: 50 nm transistor dimension

Intel's projected revenues 2003 from silicon nanotech products: > $20 Billion



Transistor for 90nm-node

Source: Intel

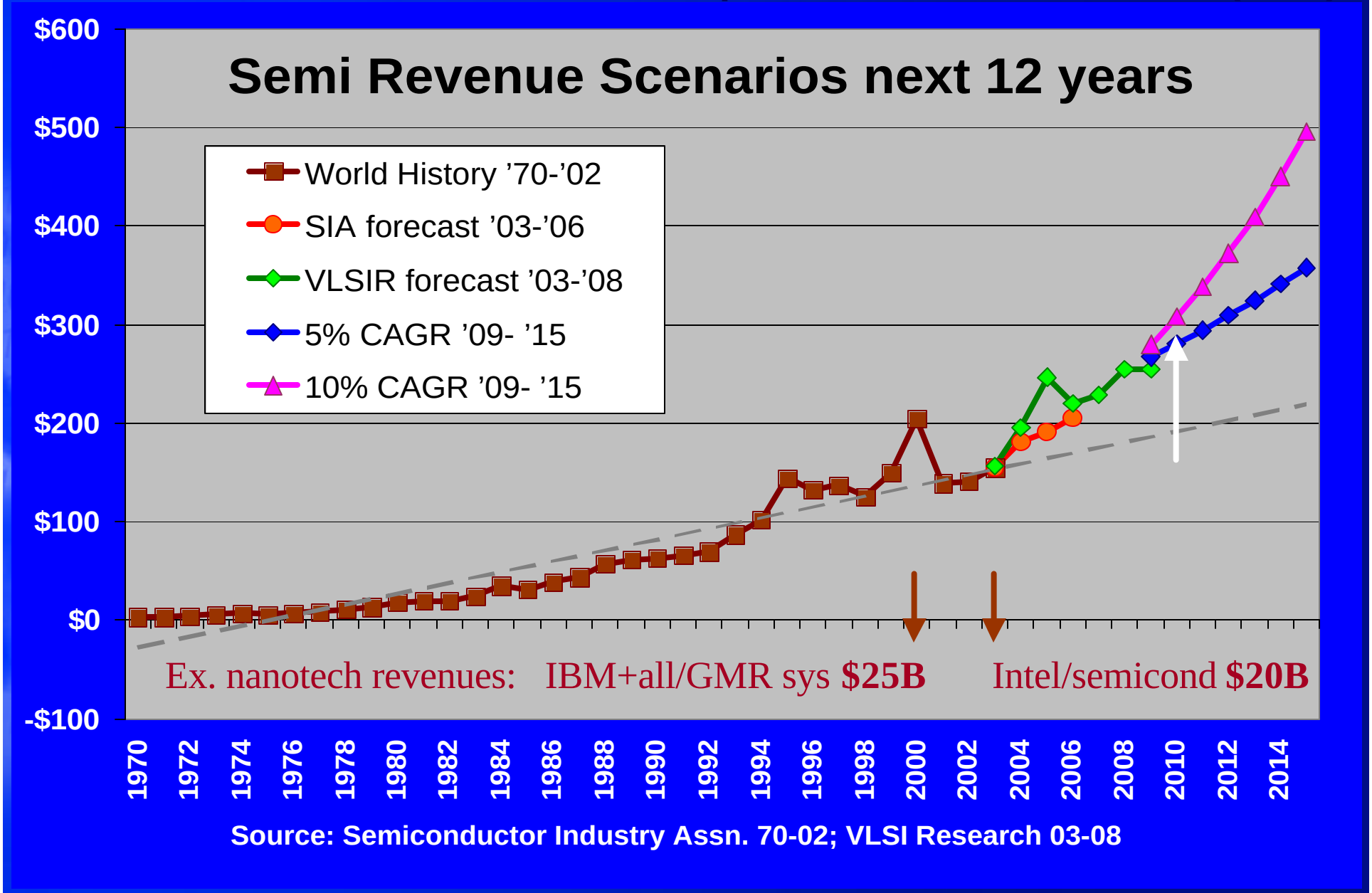


Influenza virus

Source: CDC

Gate dielectric thickness = 1.2 nm

Semiconductors Extrapolated to 2015 ($B)



Source: Semiconductor Industry Assn. 70-02; VLSI Research 03-08

Note: $300B nanotech revenues sooner than predicted (2010 instead of 2015)

NNI implementation plan published in July 2000

Major changes in the first 3 years of NNI (Part 1)

- **Research**: NNI supports about 2,500 active awards in about 300 academic organizations in all 50 states; Developments faster than expected: Reducing the time of reaching commercial prototypes by at least of factor of two for several key applications
- **Education**: 7,000 students and teachers trained in 2003; All science and engineering colleges have introduced courses related to NSE
- **Significant infrastructure**: in over 60 universities with user capabilities; Five networks (NCN,NNIN, OKN, DOE, NASA) have been established.

Scientific Breakthroughs
in the first two years (NNI, 2001-2002)

- **Developments faster than expected**

  Reducing the time of reaching commercial prototypes by at least of factor of two for several key applications

- **10 key advancements set up in 2000**

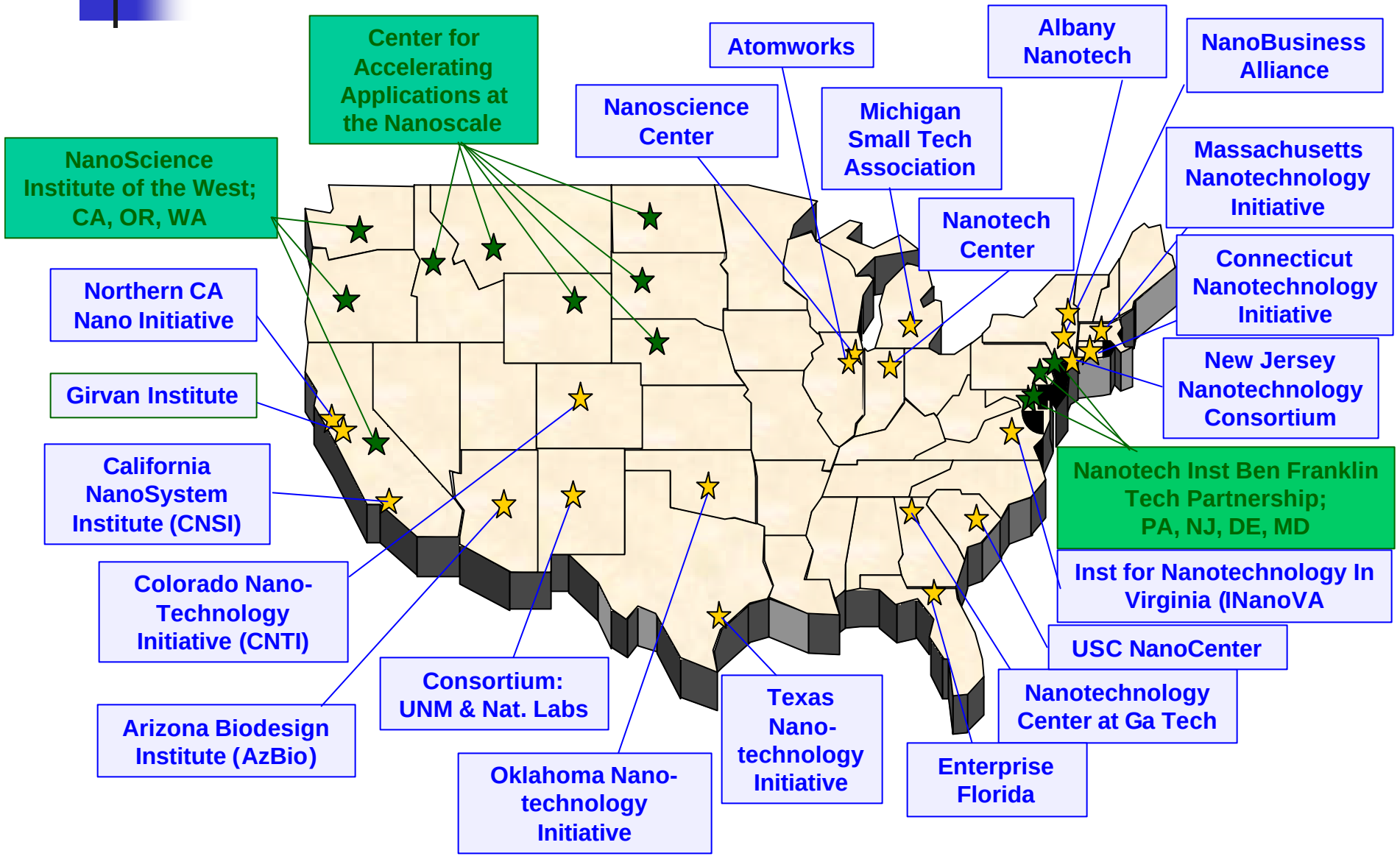
  - Engineer materials with atomic precision using biosystems as agents
  - Create circuits with the logic element a molecule wide
  - Assemble DNA, nanocrystals to build molecular devices and systems
  - Detect anthrax, other contaminants with unprecedented speed
  - Single molecule behavior and interaction
  - Artificial genetic system
  - Conducting polymers
  - New concepts for large scale production of nanotubes, their use
  - Drug delivery systems
  - Detection of cancer

NNI implementation plan published in July 2000

Major changes in the first 3 years of NNI (Part 2)

- **Industry:** about the same level of investment as NNI in medium and long-term research; Investment by large companies; From "if?" to "how?" and "who will lead?"
- **Innovation and venture funding:**
  US has over 6,000 patents in 2002 with USPTO (75% world)
- **Estimation on revenues from nanotechnology:**
  Reaching $1trillion in 2015 worldwide, and the estimations moving closer because of accelerated development; growth >25% per year
- **States and regional alliances:** "meltdown" in 2002 -
  > 20 states committed funding, > 22 regional alliances

Sampling of Current Regional, State, & Local Initiatives in Nanotechnology



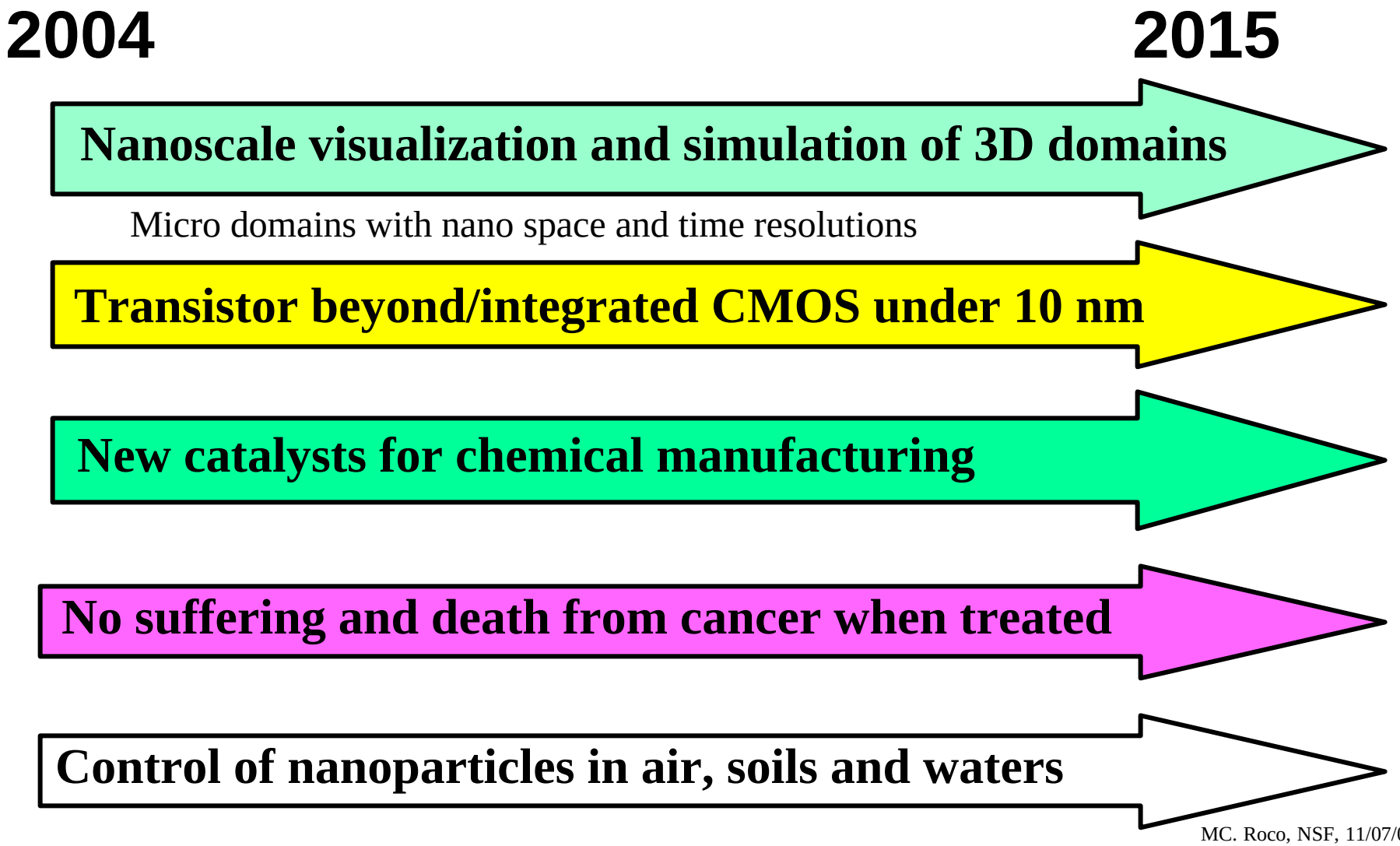
NNI implementation plan published in July 2000

Major changes in the first 3 years of NNI (Part 3)

- **Professional societies**: Specialized divisions, workshops, education; AAAS, ACS, APS, MRS, ASME, AIChE, IEEE, AVS, other major societies in the race
- **Government investment**: Worldwide investment has increased 7 times in 6 years reaching $3B in 2003 (of which US $0.77B and NSF $0.22B)
- **Societal implications from the beginning**: Workshop on Societal Implications of Nanoscience and Nanotechnology in 2000; NSF programs on SI since 2000
- **Other broader implications**: In Federal Government (NNI), Legislative (5 year Bill), Judiciary branches, cultural

After 3 years of NNI:

New R&D potential targets for 2015 (2)



Challenge: To Eliminate Suffering and Death Due to Cancer – 2015

"A Vision Not a Dream!" by using nanotechnology, A v. *Eschenbach, NCI*

Where We Want To Be ← **Where We Are**

Detection and Diagnosis

Detection and Diagnosis

Malignant Tumors With Metastases

Year 0 Year X Year Y Year Z

Prevention

Prevention

Cancer results from accumulation of multiple genetic changes in a cells.
Nanotechnology will allow earlier detection and prevention (Year 0)

After 3 years of NNI:

New R&D potential targets for 2015

2004 2015

Advanced materials and manu.: ½ from molecular level

Pharmaceuticals synthesis and delivery: ½ based on nano

Converging technologies from the nanoscale

Including: artificial organs, expand life expectancy, increase productivity

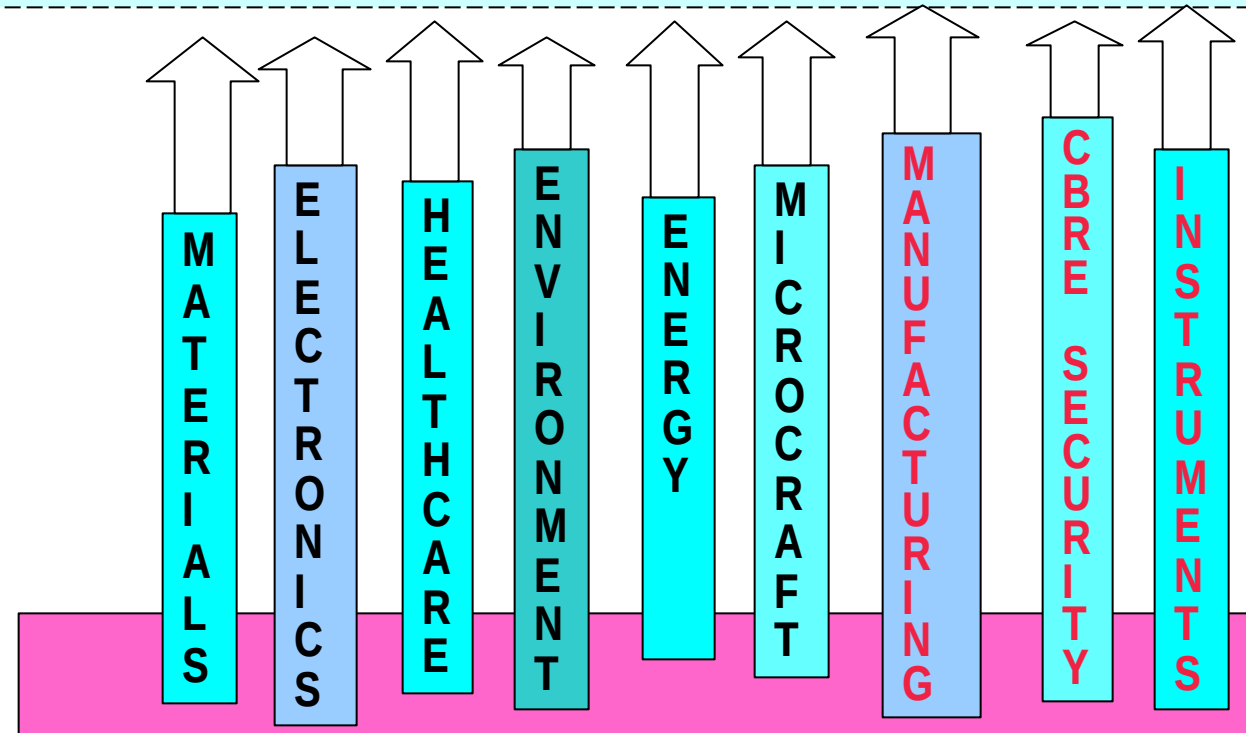
Life-cycle biocompatible/sustainable development

Education: nanoscale instead of microscale-based

MC. Roco, NSF, 11/07/03

Interdisciplinary "horizontal" knowledge creation vs. "vertical" transition from basic concepts to Grand Challenges

Revolutionary Technologies and Products



Grand Challenges

Infrastructure

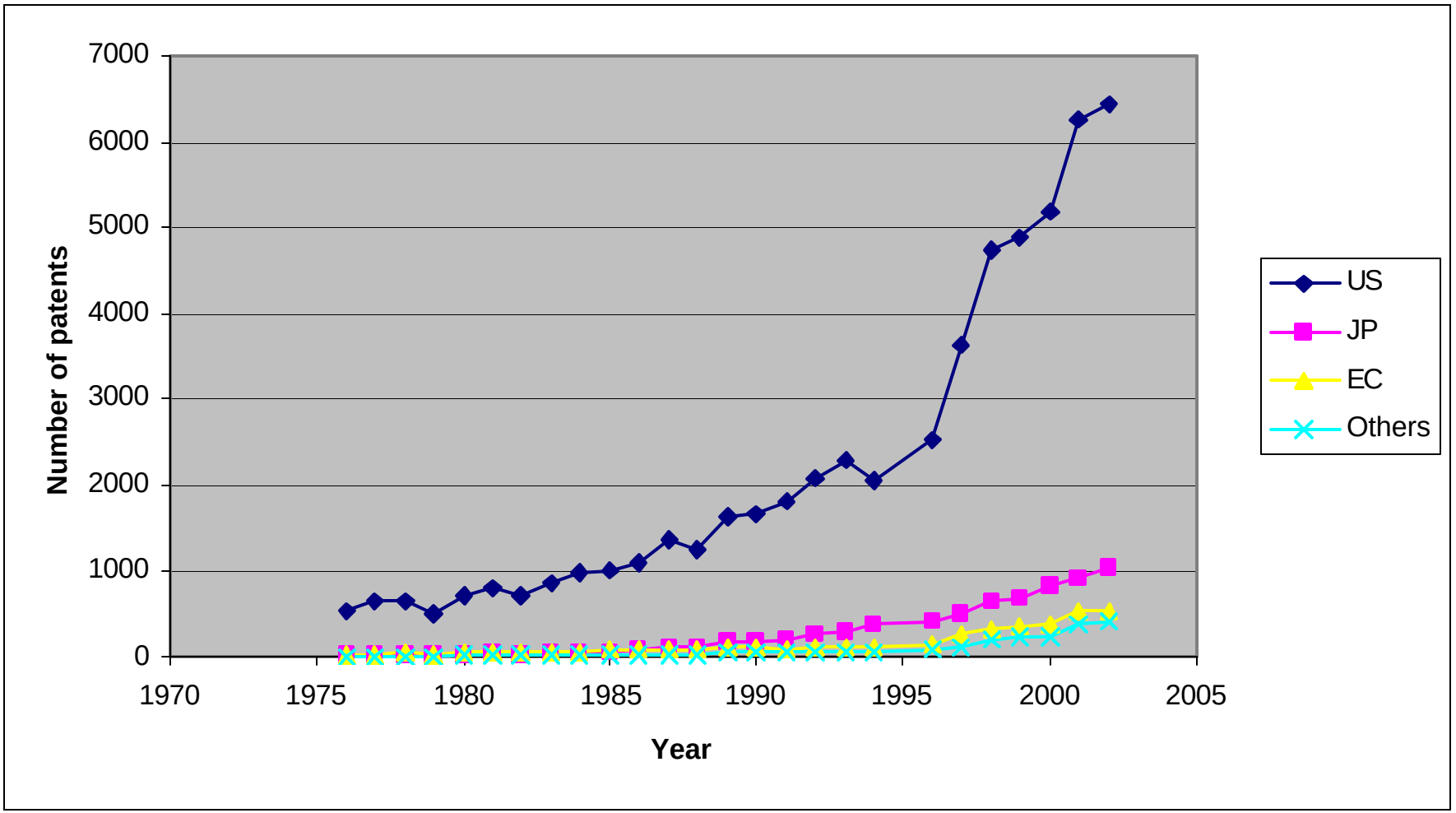
Workforce

Partnerships

M.C. Roco, NSF, 9/07/03

Nanotechnology patents per region (NSF, 2003)

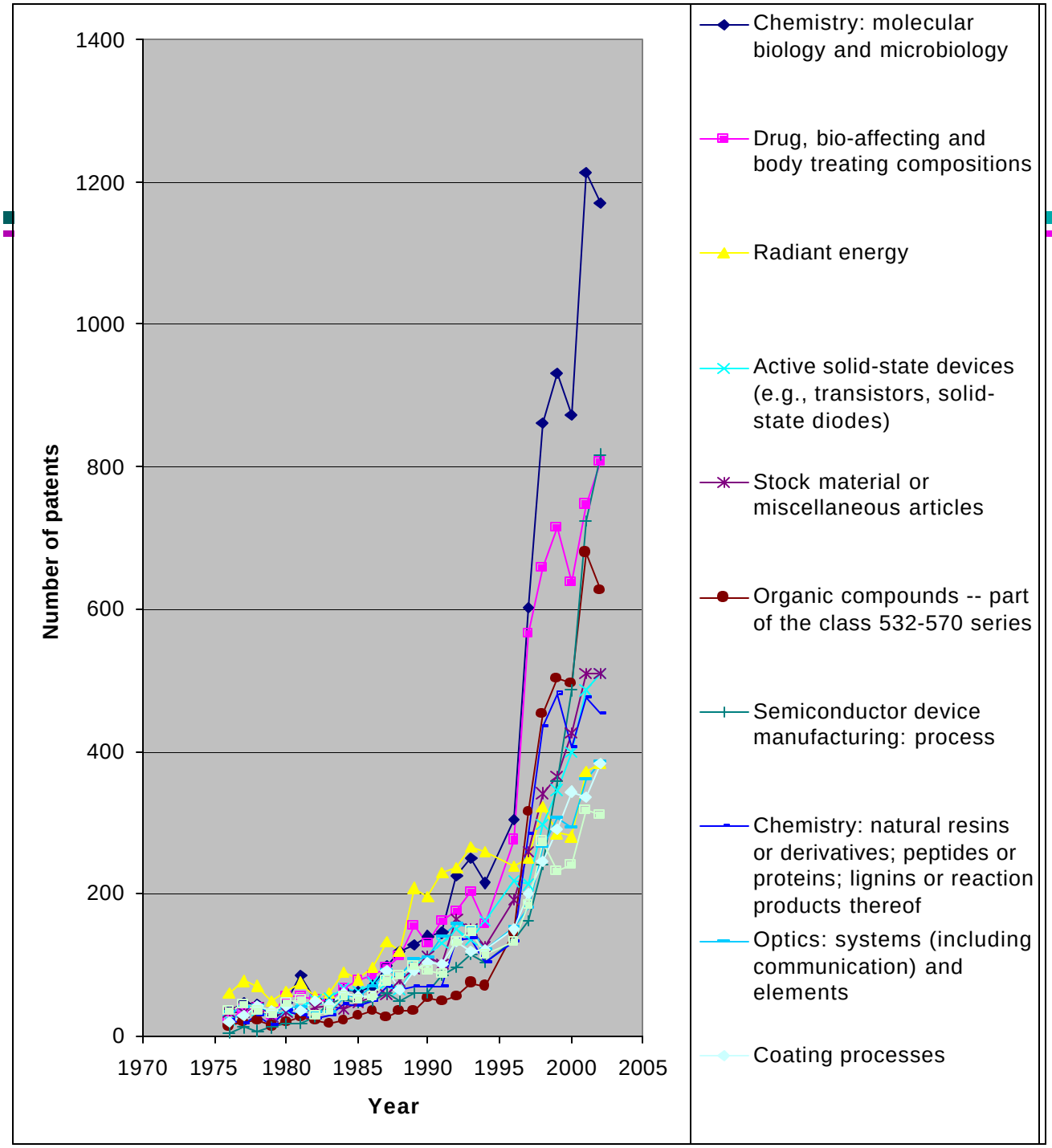
Searched by keywords at USPTO : nano*, atomic force microscop*, atomistic/molecular simulation, biomotor, molecular device, molecular electronics, molecular modeling, molecular motor, molecular sensor, quantum computing, quantum dot*, quantum effect*, scanning tunneling microscop*, selfassembl*



www.nsf.gov/nano **(from J. of Nanoparticle Research, 2003)**

MC. Roco, 9/07/03

Technology field analysis by year



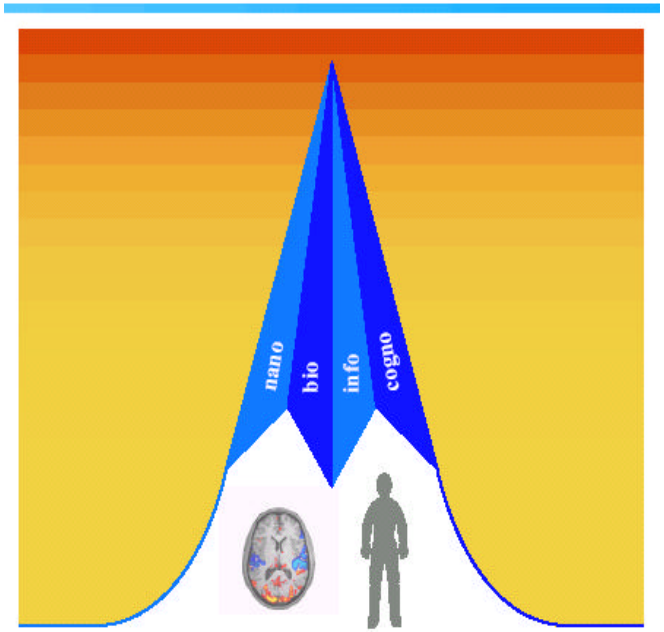
www.nsf.gov/nano

(Longitudinal Nanotechnology Patent Analysis, from J. of Nanoparticle Research, 2003)

MC. Roco, 9/07/03

Integrating science and technology from the nanoscale

- **Broad and timely opportunity**
  - **Understanding unity in nature, and technology integration from the nanoscale**
  - **Powerful transforming tools (NBIC: nano-bio-info-cogno) developing at confluence of disciplines**
  - **Improvement of individual and group human performance becomes possible**
  - **Need for anticipation ('learning before doing') and deliberate choices**
- **NBIC - agents of accelerated, synergistic change**



CONVERGING TECHNOLOGIES
FOR IMPROVING HUMAN PERFORMANCE

June 2002

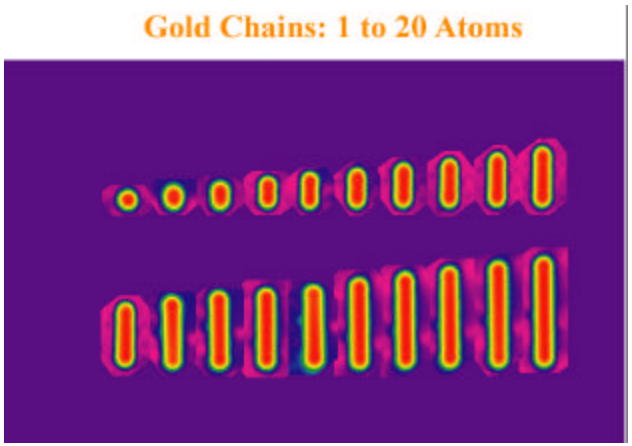
(December 2001)

Online www.nsf.gov/nano,
also Kluwer Academic Publ

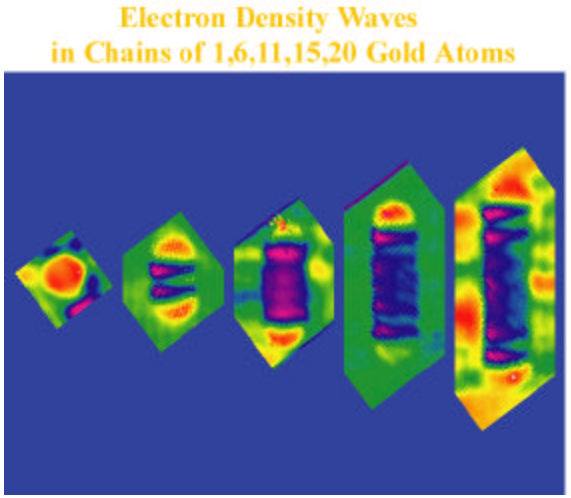
Specify the state of a molecule

EX: Atom-by-Atom Construction of Nanostructures, W. Ho et al.

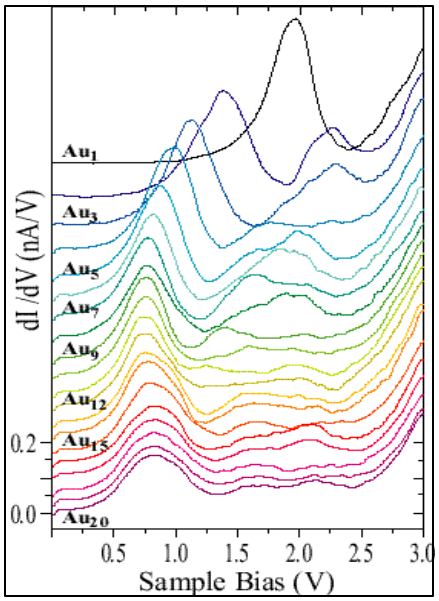
A



B



C

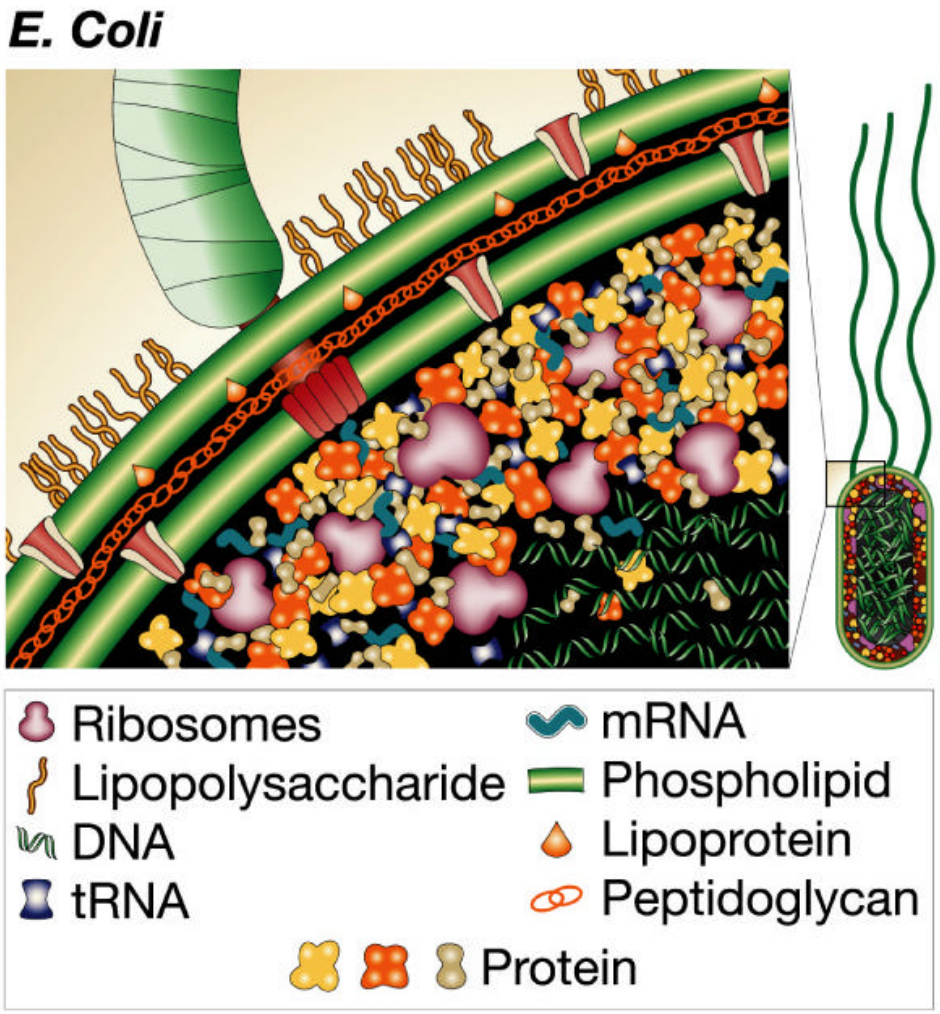


A: STM images of 1 to 20-atom Au chains constructed atom-by-atom by atomic manipulation on NiAl(110) at 12 K.

B: Electron density waves of 5 different Au chains on NiAl(110) exhibiting standing waves of 1-D particle in a box.

C: Electron density of states measured in the middle of the 1-20 atom Au chains, revealing the development of 1-D band structure from a single atomic level.

Specify the state of a cell



Measure and simulate the populations of all the proteins present

3 dimensional
Highly parallel
…

Functional Nano-Scale Bio-Materials by Controlled Self-Assembly

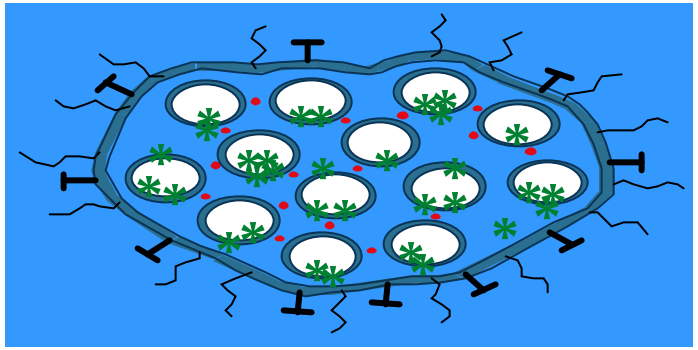
EX: Matthew Tirrell, UCSB, NSF-0103516

? Self-assembly processing of nanoscale bio-materials and devices (Creating bio-mimetic nested structures, micromachines components)

Triple Helix

? Molecules (e.g., a Triple Helix) have been designed to incorporate into bilayer walls of structures to control their interactions both with each other and with their surroundings.

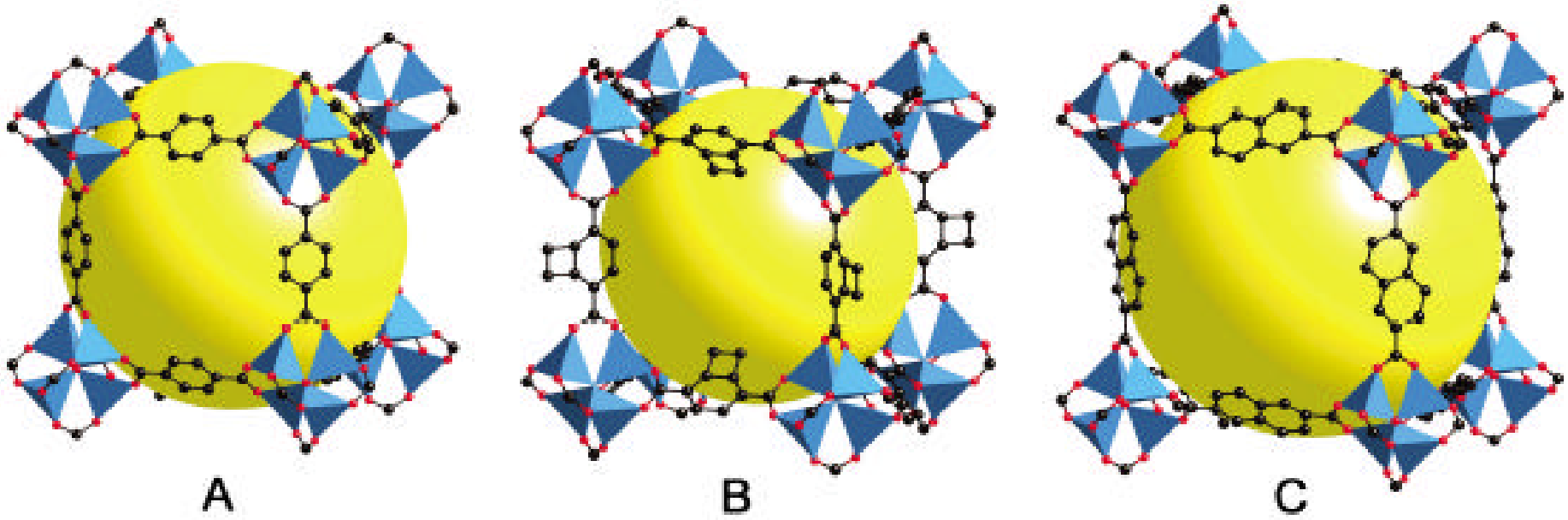
? Controllable secondary structures such as rods, tubules, vesicles, and micelles will lead to structures for functions that may not be naturally occurring or that mimic or supply interesting functionality.



Vesosomes: Vesicle-Encapsulated Vesicles

Molecular Fuel Tanks

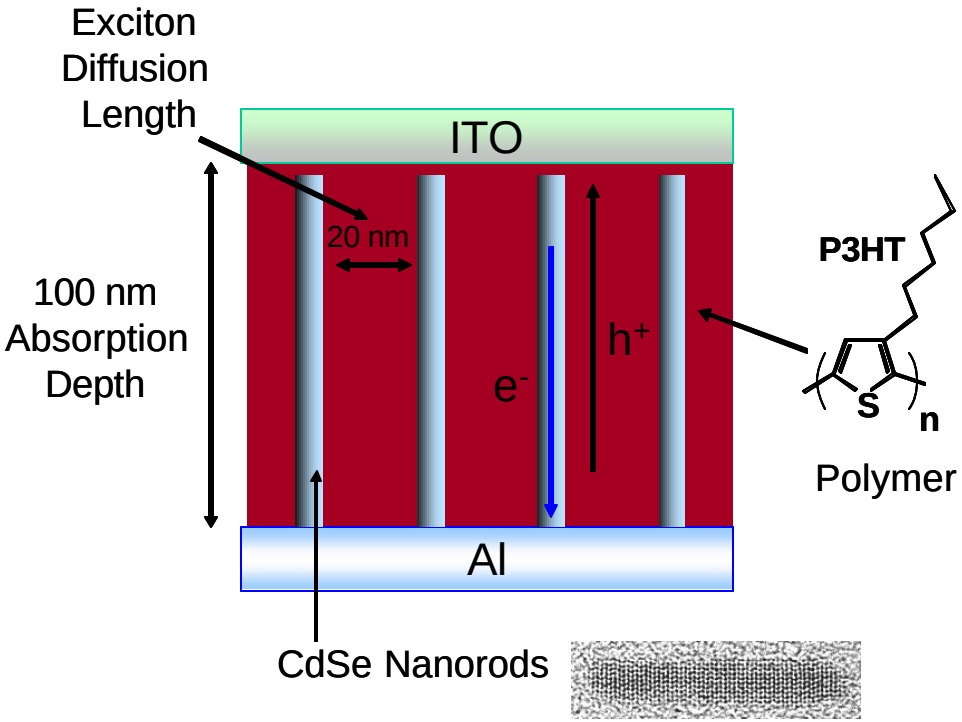
O.M. Yaghi, U. Michigan, #0242630



0.5 % **1.0 %** **2.0 %**

Uptake (wt%) of hydrogen storage in Metal-Organic Frameworks at RT and 10 bar

Energy: Schematic design of the nanorod-polymer solar cell

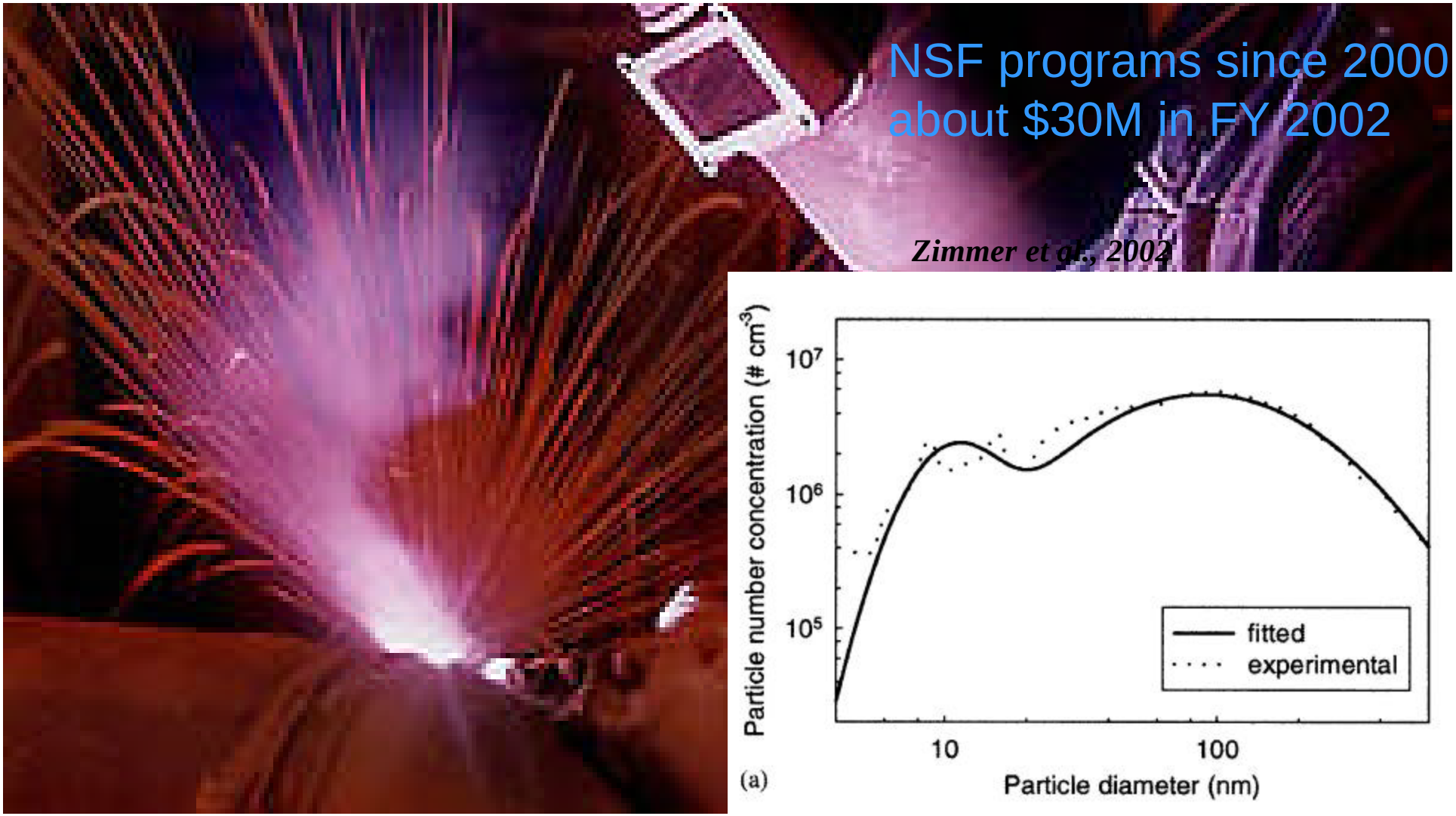


transmission electron micrograph
of a CdSe nanorod at the bottom

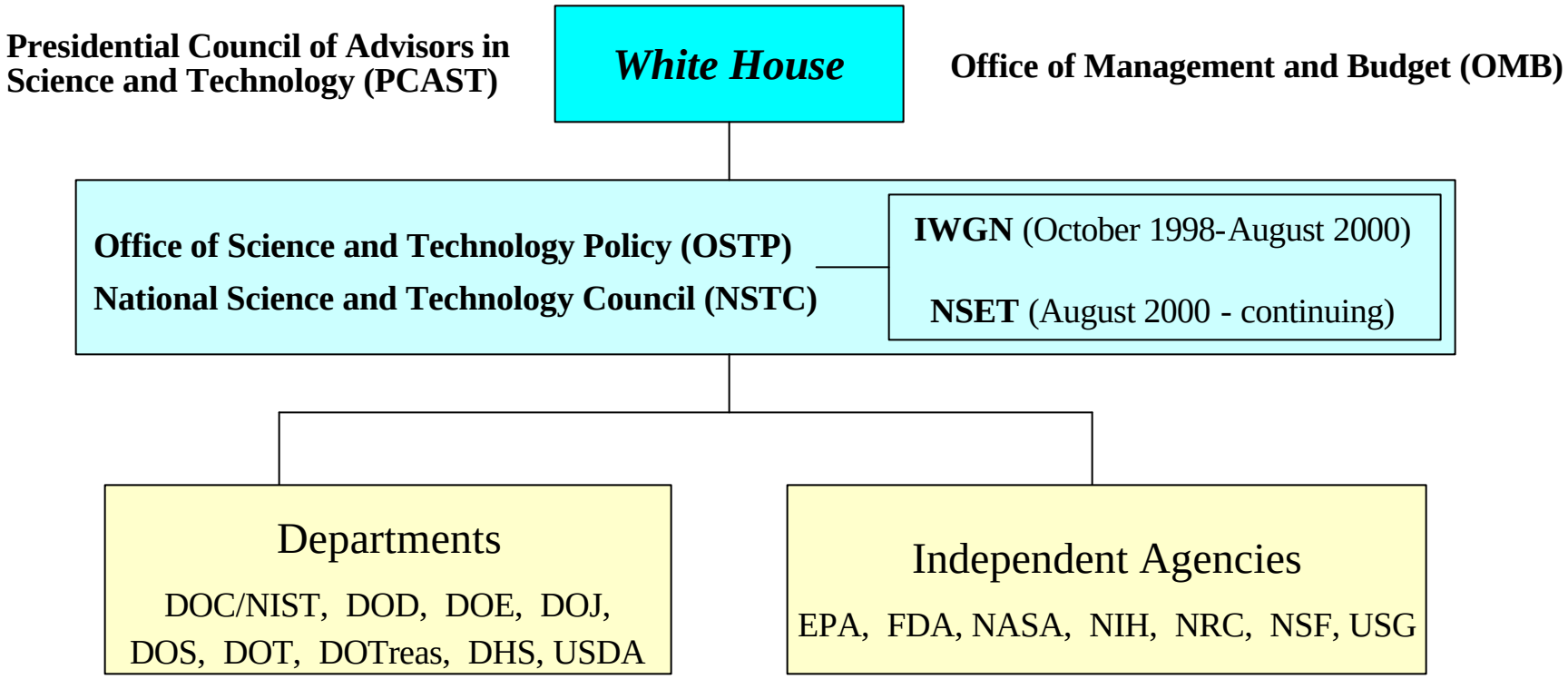
(courtesy P. Alivisatos, Univ. California, Berkeley; and Nanosys, Inc.).

Environmental issues related to nanotechnology include:

- Sustainable development, life-cycle of products, measurement and mitigation, clean-up techniques, global effects
- Combustion, welding, water/air filtration, cell behavior, toxicity



Organizations that have prepared and contribute to the National Nanotechnology Initiative (**NNI**)



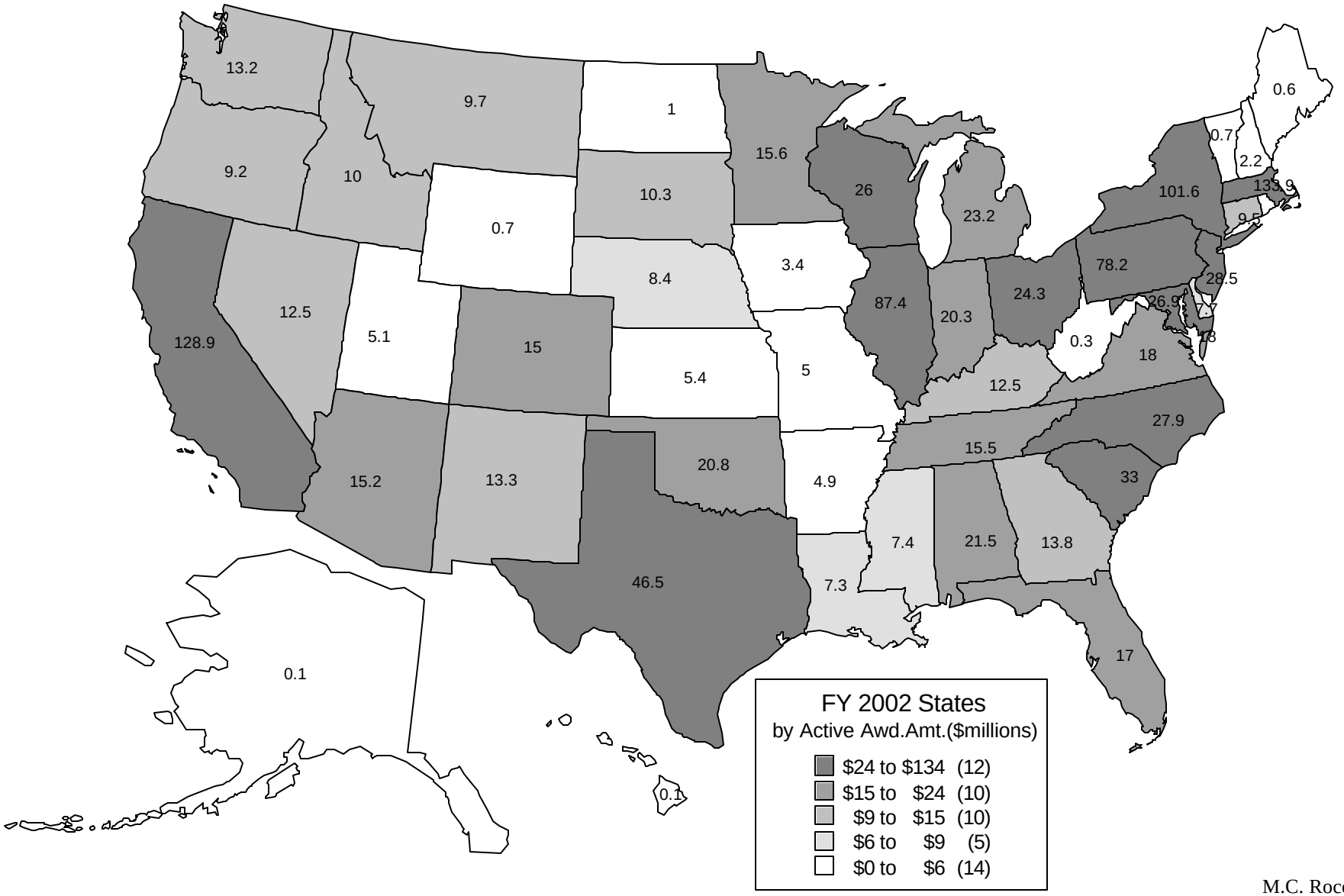
Estimation: Federal Government R&D funding NNI (~$770M in 03)
Industry (private sectors) ~ NNI funding
20 state and local (universities, foundations) ~ 1/2 NNI funding

NNI: R&D Funding by Agency

Fiscal year (all in million $)	*2000*	*2001* Enacted/actual	*2002* Enacted/actual	*2003*	2004 Request
National Science Foundation	97	150 /150	199 /204	221	249
Department of Defense	70	110 /125	180 /224	243	222
Department of Energy	58	93 /88	91.1 /89	133	197
National Institutes of Health	32	39 /39.6	40.8 /59	65	70
NASA	5	20 /22/	35 /35	33	31
NIST	8	10 /33.4	37.6 /77	66	62
Environmental Protection Agency	-	/5.8	5 /6	5	5
Homeland Security (TSA)	-		2 /2	2	2
Department of Agriculture	-	/1.5	1.5 /0	1	10
Department of Justice	-	/1.4	1.4 /1	1.4	1.4
TOTAL	270.0	422.0 /464.7	~ 600 /697	~ 770	~ 849

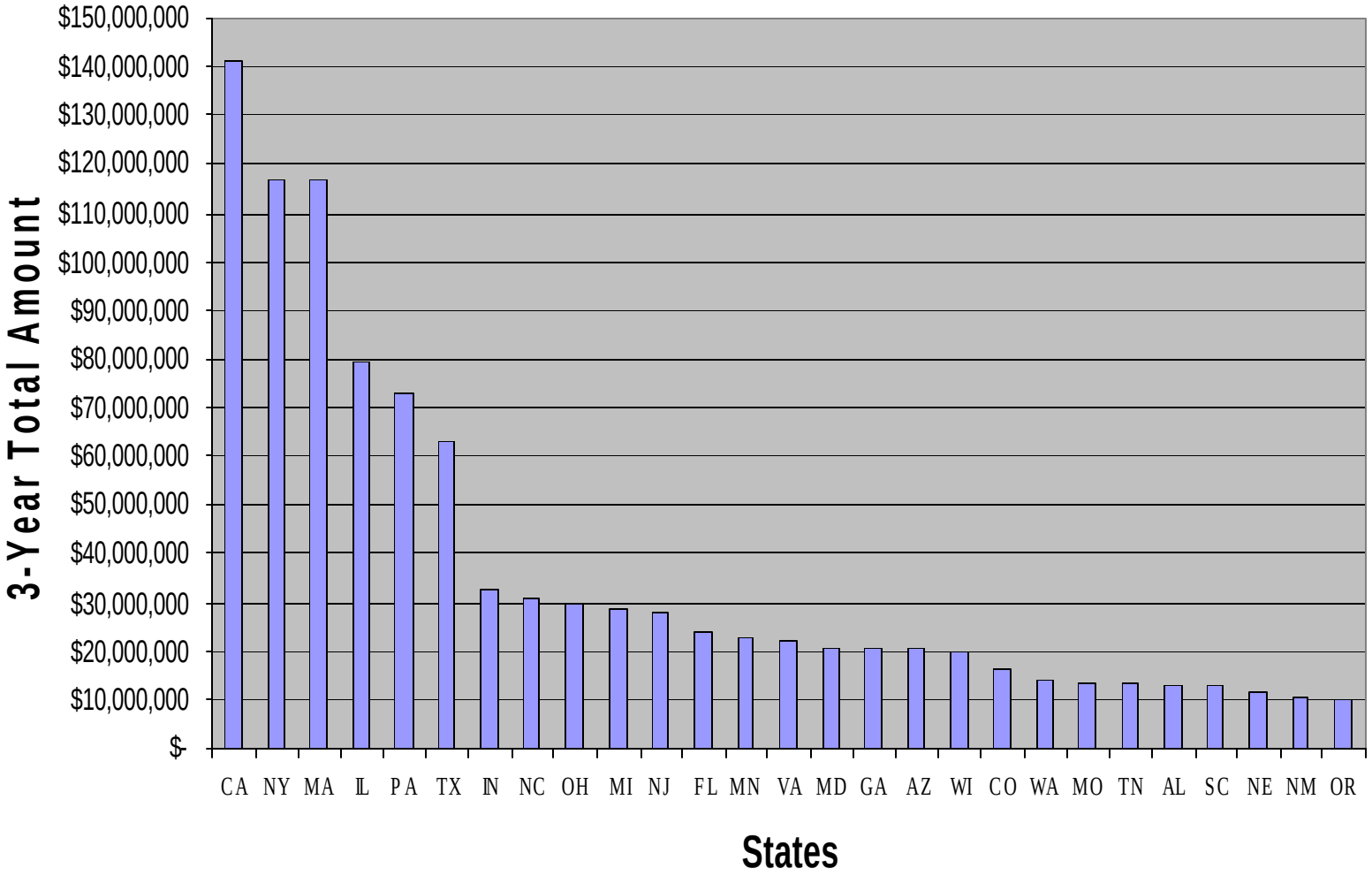
Other NNI (NSET) participants are:
OSTP, NSTC, OMB, DOC, DOS, DOT, DOTreas, FDA, NRC, DHS, IC

FY 2002 NSE active awards: Geographical distribution

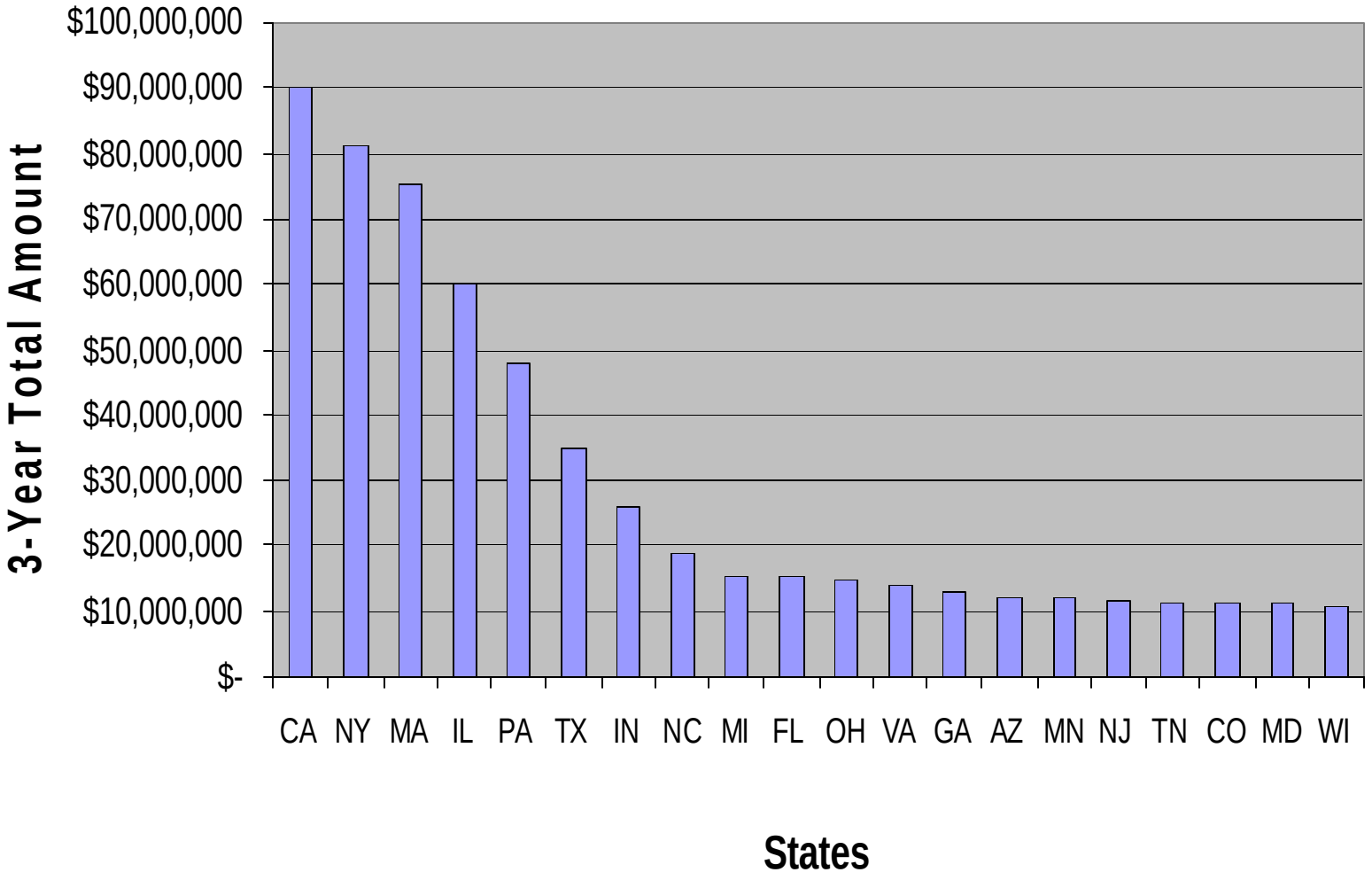


M.C. Roco, 10/09/03

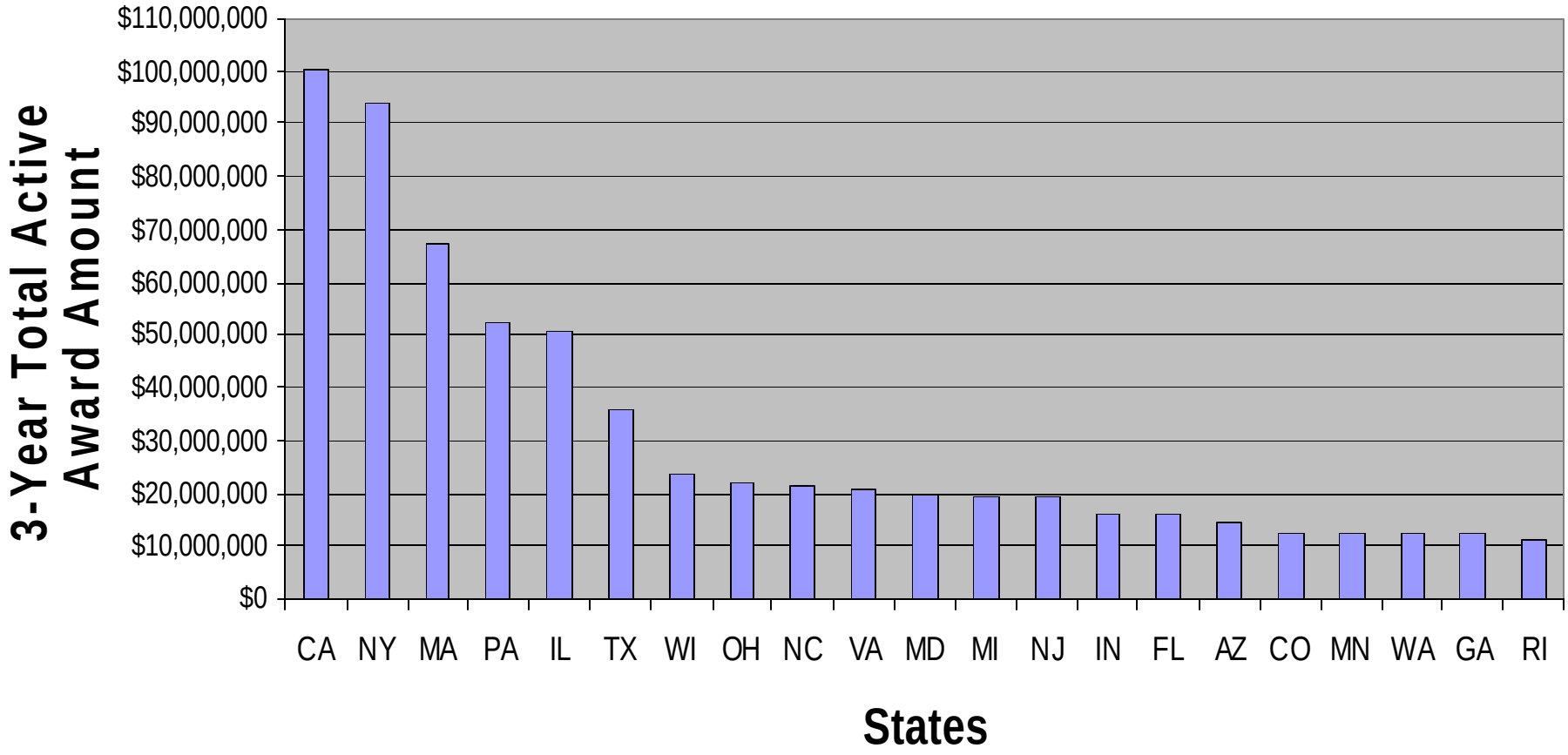
States Awarded $10 million or More by NSF for NEW NNI Research during FY 2001-2003



States Awarded $10 million or More by NSF for NEW NNI Research during FY 2001-2003 (through 6/30/03)

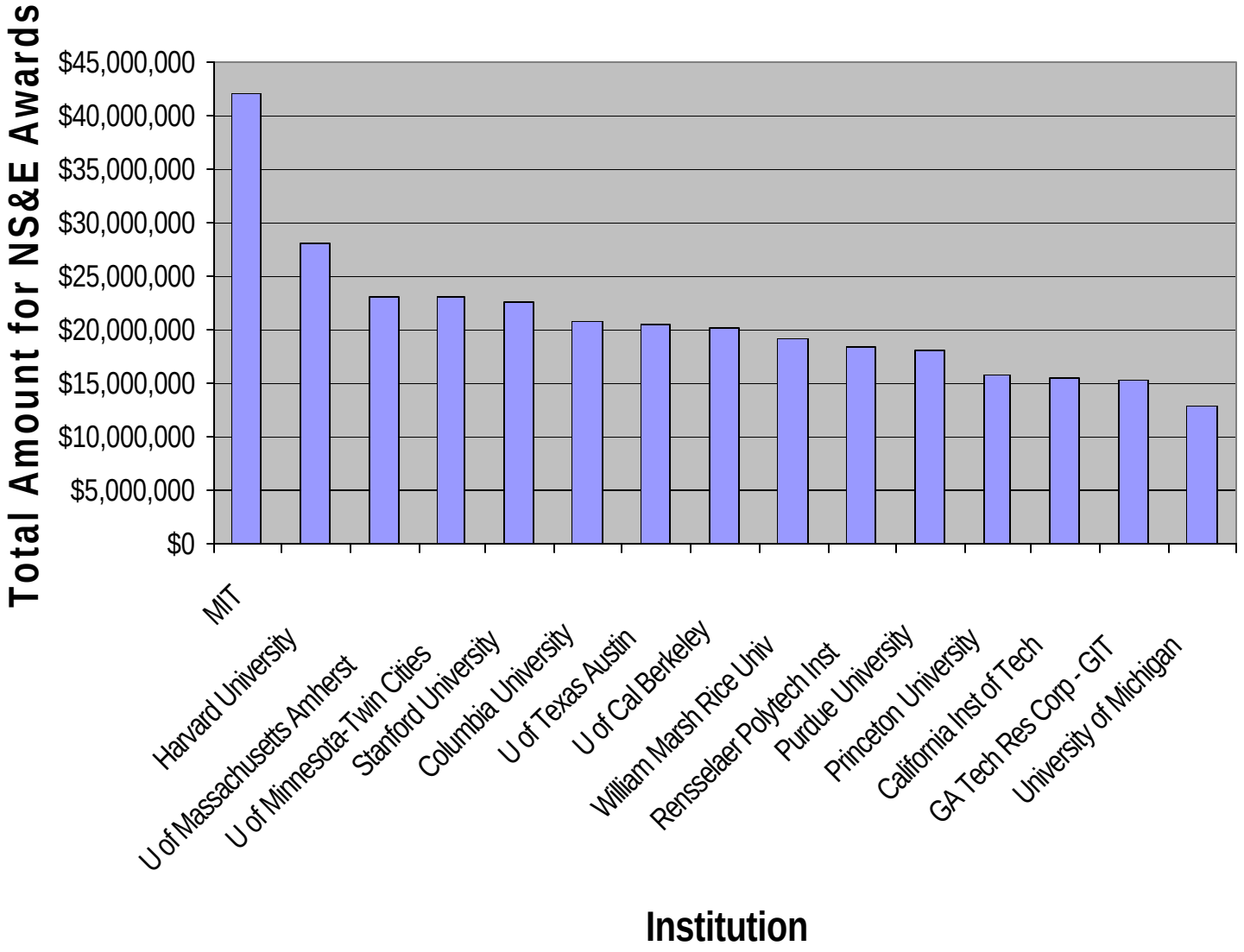


States with ACTIVE NSF-Supported NNI Research Awards Totaling $10 million or more during FY 2001-2003



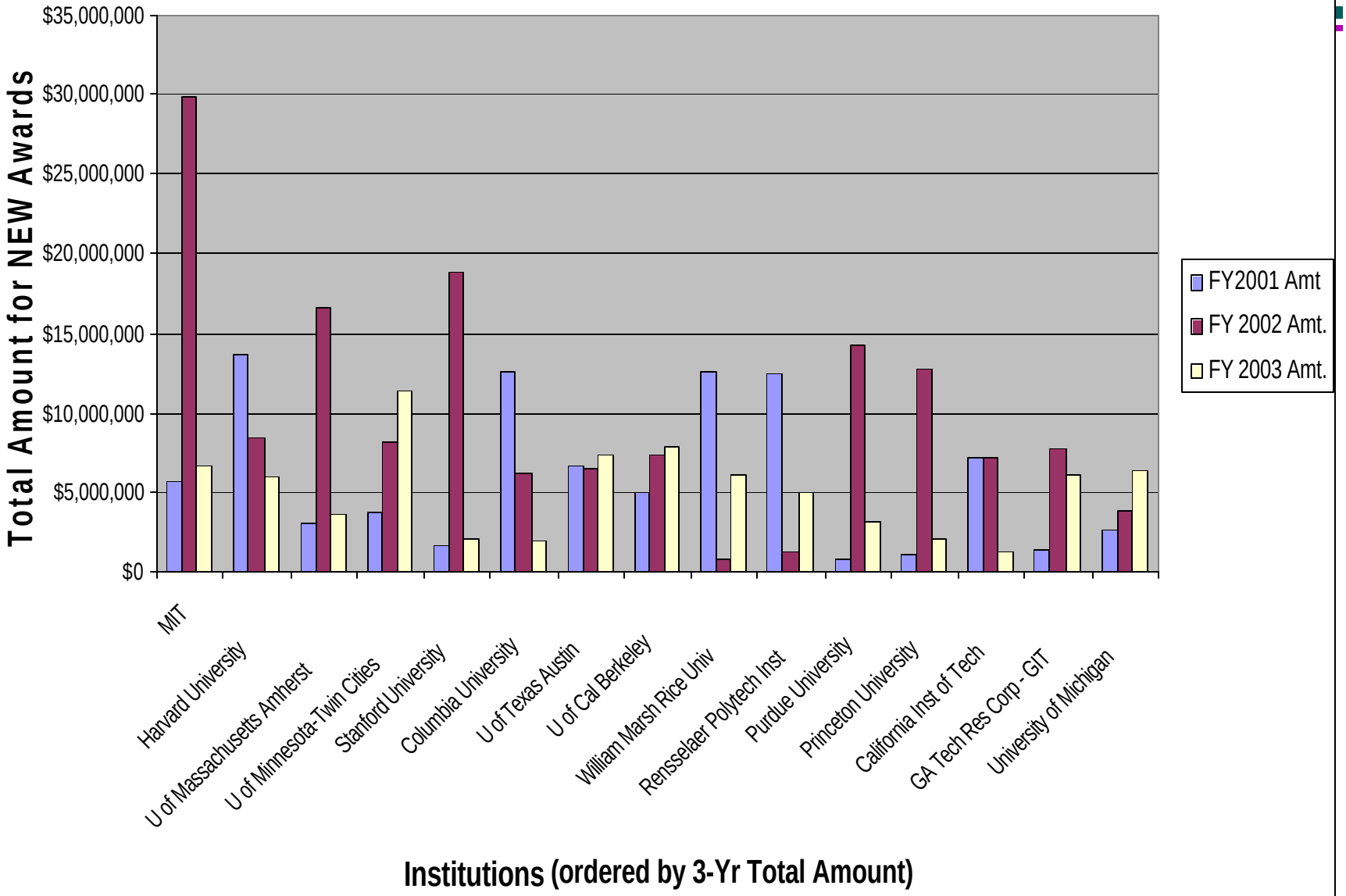
NSF FY 2001-2003

NEW Nanoscale S&E Awards for Top 15 Institutions by Total Amount

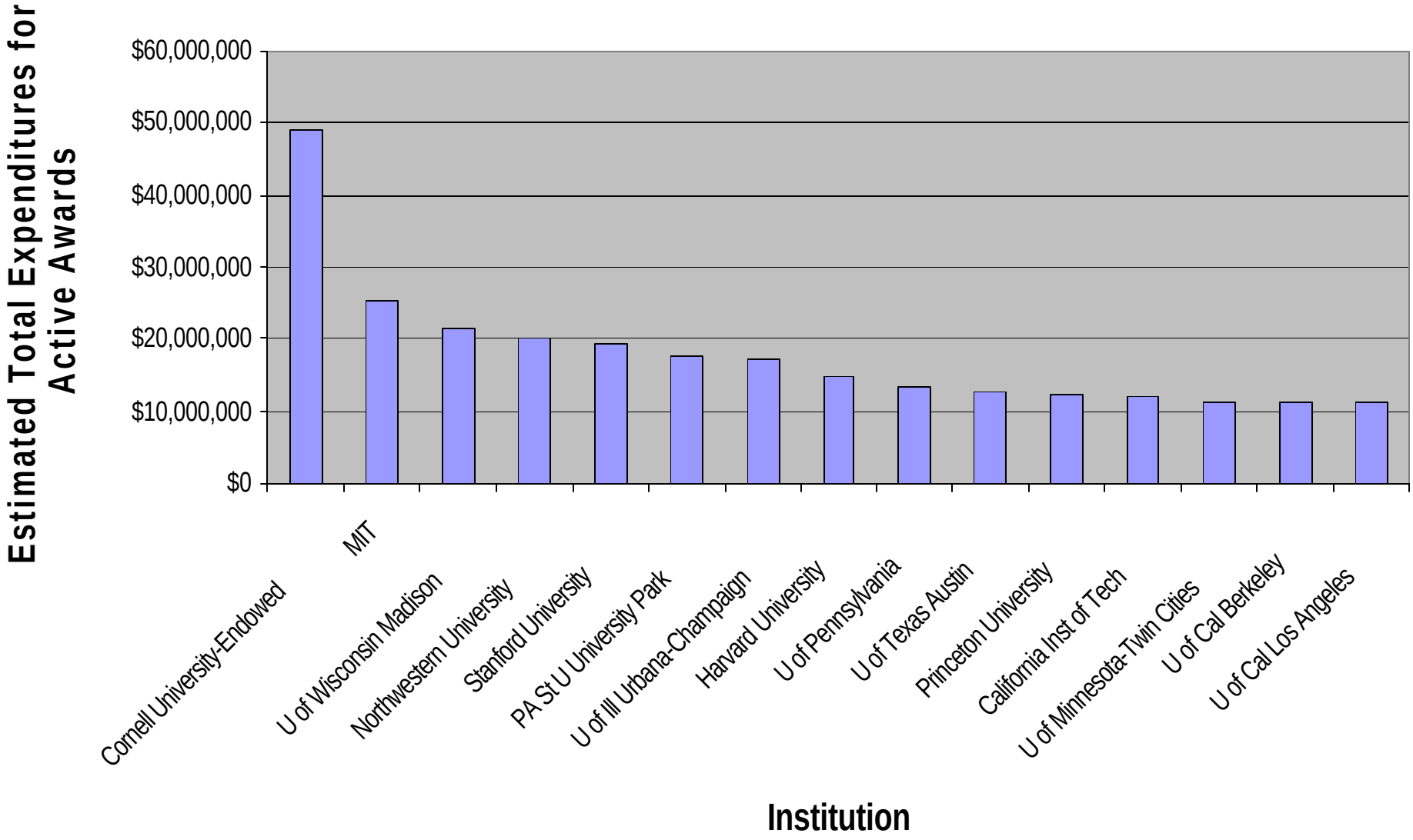


NSF FY 2001-2003

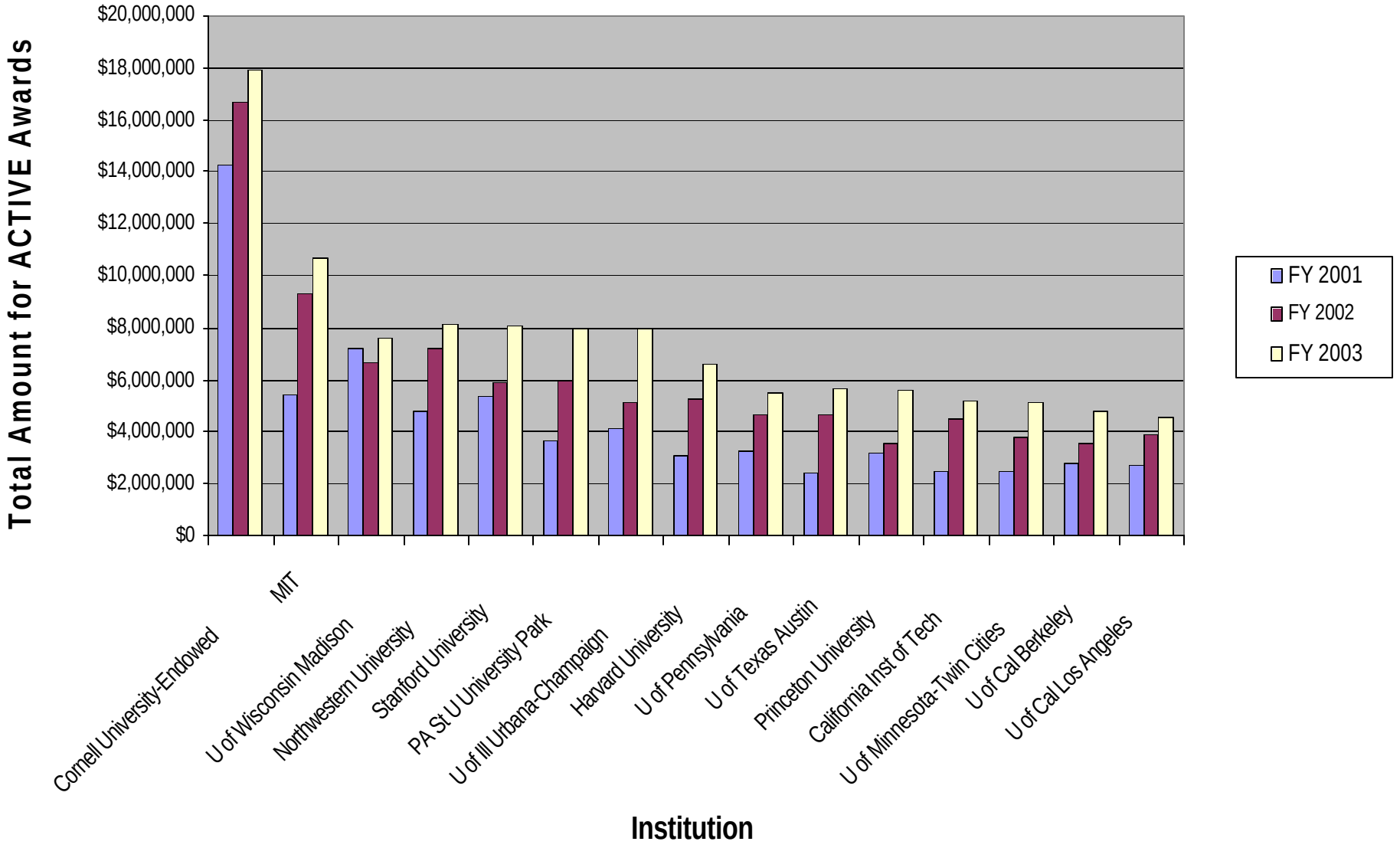
NEW Nanoscale S&E Awards for Top 15 Institutions by Total Amount



3-Yr Total Amount for ACTIVE Nanoscale S & E Awards (FY 2001-2003)

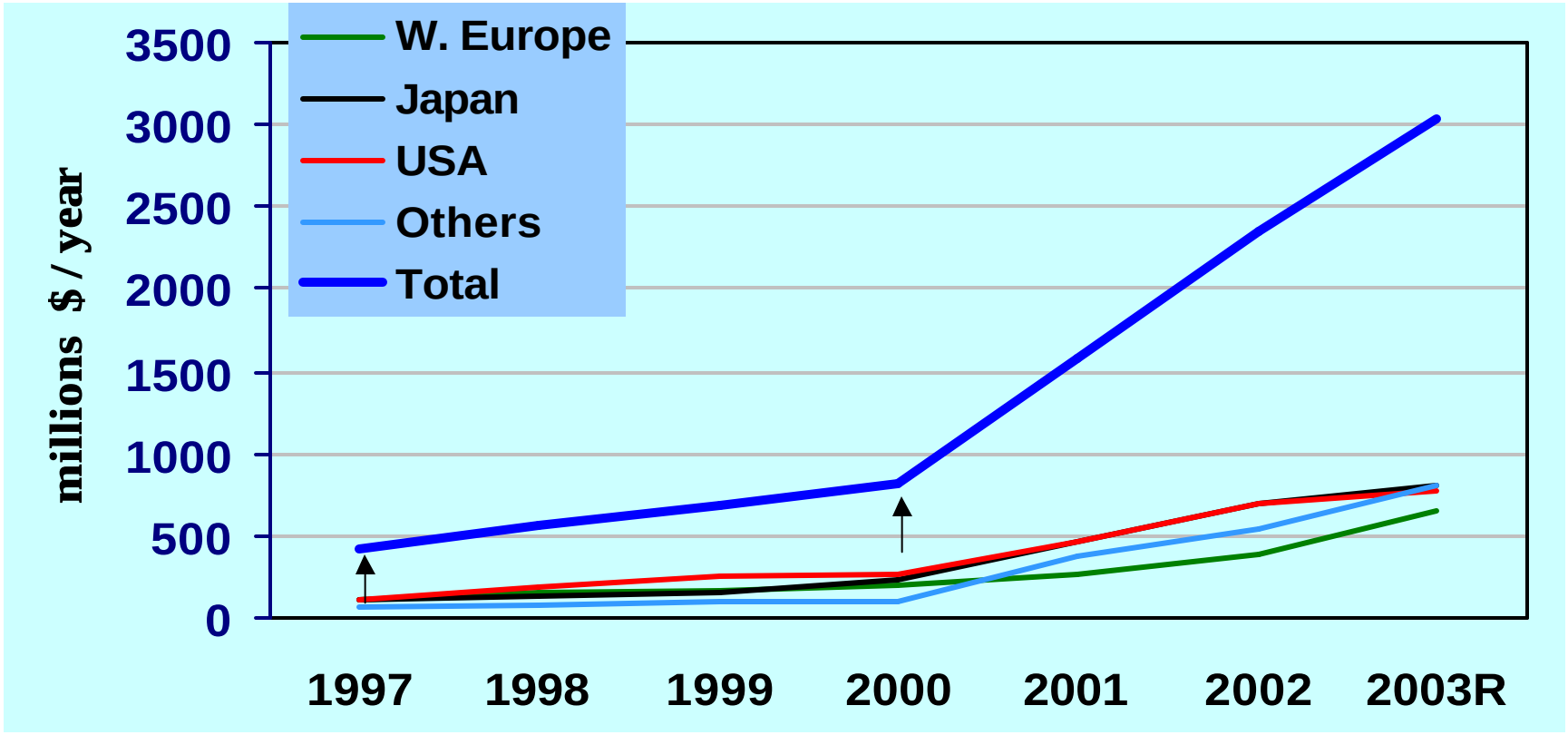


ACTIVE Nanoscale S&E Awards for Top 15 Institutions by Total Amt. per FY (2001 -2003)



Context – Nanotechnology in the World

Government investments 1977-2003 (estimation NSF)



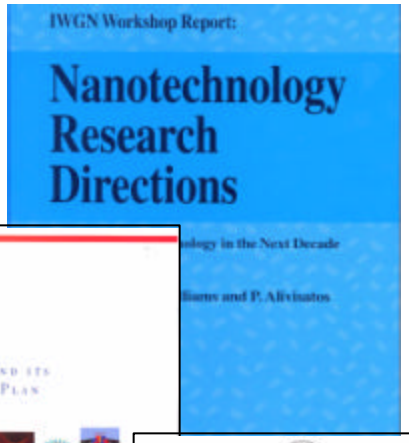
Note:

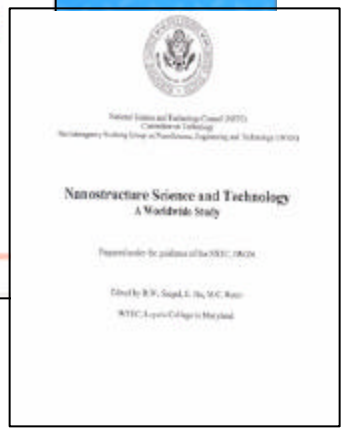
- U.S. begins FY in October, six months in advance of EU & Japan (in March/April)

Defining the vision

National Nanotechnology Initiative

1999:
10-year
vision

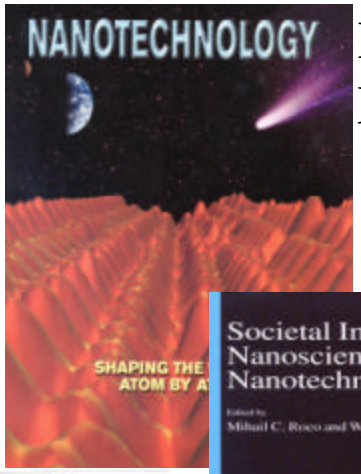




Government
plan

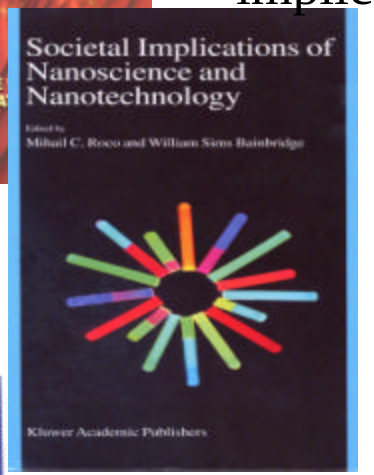
Worldwide
benchmark

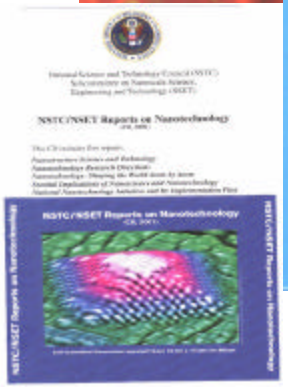
Reports



Brochure for
public

Societal
implications

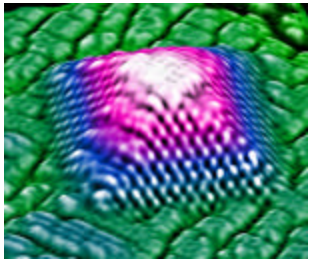




June 2002: "Review of NNI" by U.S. Academies for WH/OSTP

April 2003: "FY 2004 NNI and Its Implementation Plan", NSET

In preparation: Updated 10 year vision



Planning for the future: expanding the frontiers of nanotechnology

Workshops for receiving input from the community (examples):

- **Nanostructured materials "by design" - Workshops on 10/02, 06/03**
- **Catalysts that function at the nanoscale - 06/03**
- **Nanoelectronics, optoelectronics and magnetics - 11/02, 2/04**
- **CBRE protection and detection - 05/02**
- **Advanced healthcare, therapeutics, diagnostics - 06/00**
- **Nano-biology and medicine - 10/03**
- **Environmental improvement - 06/02, 08/02, 07/03, 09/03**
- **Efficient energy conversion and storage - 10/02, 02/03**
- **Microcraft space exploration and industrialization - Spring 04**
- **Manufacturing processes - 01/02, 05/02; Instrumentation – 01/04**
- **Agriculture and food systems - 11/02; Converging Technologies – 09/03**
- **Societal implications (II) - 12/03; Education (NSEE) – 09/03**

"Nanotechnology Research Directions (II)" - Spring 2004

Revisit the NNI long-term vision formulated in January 1999

R&D focus in 2003

- **Growing area towards technological innovation**
  - **Materials, including bulk, coating, dispersed systems**
  - **Chemicals, including catalysts**
  - **Pharmaceuticals**
  - **Electronics**
- **Emerging areas to be addressed in the NNI plan**
  - **Nanomedicine**
  - **Energy conversion and storage**
  - **Agriculture and food systems**
  - **Molecular architectures**
  - **Realistic multiphenomena/multiscale simulations**
  - **Environmental implications**
  - **Converging technologies from the nanoscale**

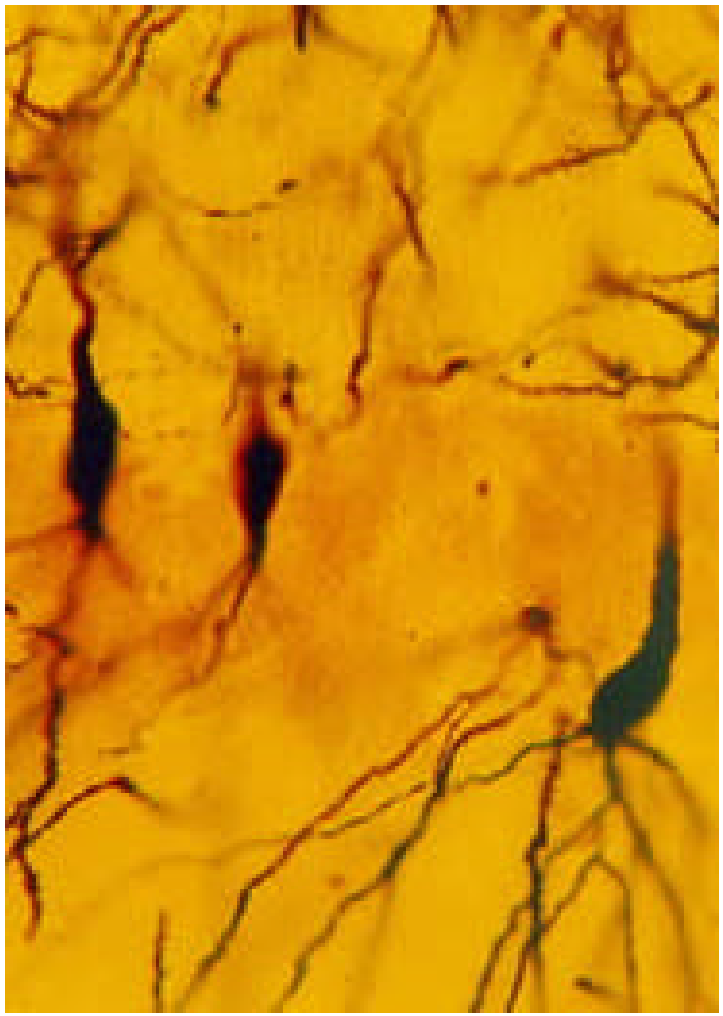
Improving human performance: by technology integration from the nanoscale

- **Expanding human cognition and communication**
- **Improving human health and physical capabilities**
- **Enhancing societal outcomes, incl. new products**
- **National security**
- **Unifying science and education**
- **Reshaping organization and business**

Other societal outcomes, implications

Successive breakthroughs

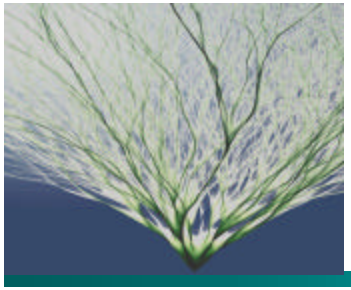
Lasers operate inside single cells



Nanosurgery vaporizes cellular components leaving rest intact

- **Cut a nerve connection without killing it**

Harvard U. (Nature, October 2003)



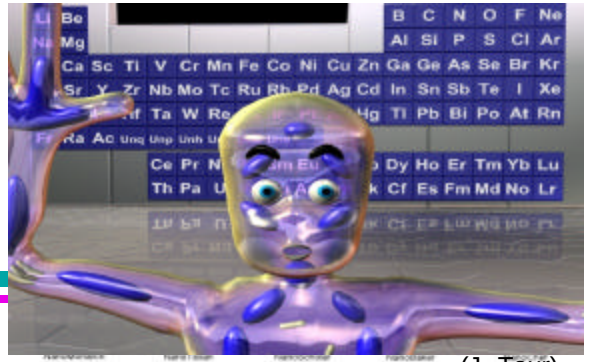
Outcomes of 2001-2003: R&D Networks and User Facilities

- **Network for Computational Nanotechnology** (NCN)
  - **7** universities (Purdue as the central node)
  - Nanoelectronic device simulation/modeling
- **National Nanotechnology Infrastructure Network (NNIN)**
  - User facility
  - Development measuring & manufacturing tools
  - Education and societal implications
- **Oklahoma Nano Net (EPSCoR award)**
- **DOE network for large scale facilities**

22 new centers and networks supported by NNI since 2001:

10 NSF, 3 DOD, 5 DOE, 4 NASA (at universities); continuing MRSECs

Education and Training


(J. Tour)

- **Integrated research and education - Make Every Lab a Place of Learning: <u>Aiming at systemic changes</u>**
  - ~ 7,000 students/year, technicians, teachers, and faculty in 2003
- **Curriculum development: <u>New foundation</u>, <u>Training earlier</u>**
  - Nano- instead of micro-based; From elementary schools to continuing education (Undergraduate education ~ 33 awards in FY 2003; Expand to K -12 education in 2004); Industry fellowships
- **All NSF centers have <u>education and outreach programs</u>**
  - Including science museums Boston, Chicago, Milwaukee, LA
- **<u>International education opportunities</u>**
  - Young researchers to Japan and Europe; REU sites; attend courses abroad; PASI - Latin America, NSF-E.C.; bi-lateral workshops and exchanges

Nanotechnology Undergraduate Education (NUE)

New component of the 2003 NSF Nanoscale Science and Engineering (NSF 02-148) program is focused on:

- Introductory undergraduate courses presented through the development of text, software, laboratory and demonstration experiments, and web-based resources;
- Development and dissemination of new teaching modules for nanoscale science and engineering that can be used in existing undergraduate courses, particularly during first and second year studies.

33 awards in FY 2003 (www.nsf.gov/nano)

Reviewed by the NSF workshop on September 11-12, 2002 at NSF (www.nanofab.psu.edu/education/nsf-nue-program.htm)

Nanoscale Science and Engineering Education program (NSF 03-044, new in FY 2004)

NSEE to produce systemic changes in nanoscale science and engineering education. $12M in FY 2004. Components:

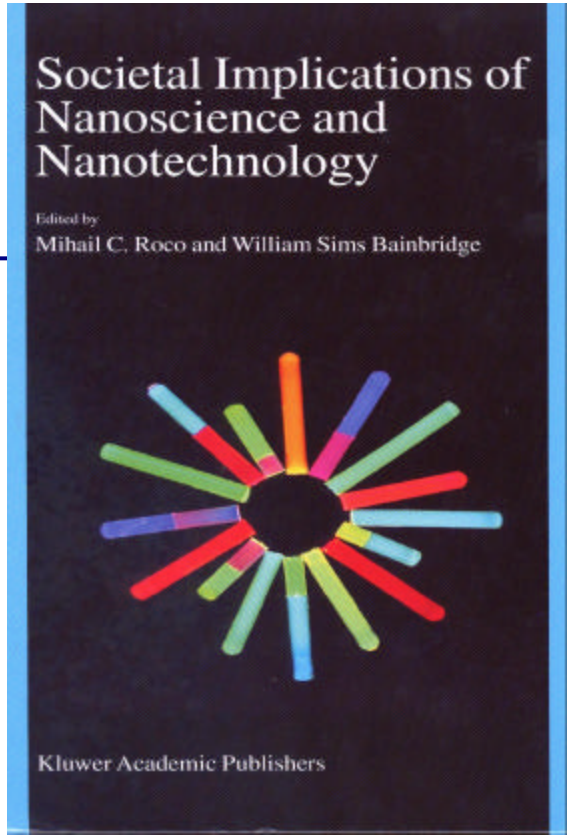
- **Centers for Learning and Teaching (NCLT):** Create educational leadership for nanotechnology education (doctoral programs representing collaborations of researchers in nanoscale science and engineering, education, and cognitive and behavioral sciences)
- **Informal Science Education (NISE):** Foster public awareness and understanding of nanoscale science and engineering through development of media projects (film, radio, television) and exhibits.
- **Instructional Materials Development (NIMD):** Support development of prototype instructional materials that promote student learning and interest in nanoscale science, engineering, and technology concepts for grades 7-12.
- **Nanotechnology Undergraduate Education (NUE):** Introduce nanoscale science and technology through a variety of interdisciplinary approaches into undergraduate education, particularly in the first two collegiate years.

K-12 NANOTECHNOLOGY
Illustrations of Education Modules

- **University of Wisconsin - Art Ellis: Nanoworld for kids**
- **Northwestern University – Bob Chang: Virtual NT Encyclopedia**
- **Rice University – James Tour: NanoKids**
- **Cornell University: for nanobiotechnology, and nanoelectronics**
- **Northwestern University, Chicago: for materials, public museum**
  - **Harvard University: for nanosystems, public museum**
- **UNC Nanomanipulator by high school students**
- **Purdue NanoHub (www.nanohub.purdue.edu)**
- RPI "Molecularium" and "Nanoscope" for K-12 students

NSF plans to have 10 K-12 education modules in 2004

Societal Implications: Follow-up of the September 2000 report



http://nano.gov

- **Make support for social, ethical, and economic research studies a priority:**
  (a) New theme in the NSF program solicitations;
  (b) Centers with societal implications programs;
  (c) Initiative on the impact of technology, NBIC, HSD
- **NNCO – communicate with the public and address unexpected consequences**
- **Basic reference for the interaction with the public**
- **Taking faster advantage of the benefits**
- **Converging technologies from the nanoscale**
- **International workshop with EC (2001); Links to Europe and Asia**

State participation

Illustrations from 20 states

CA	California NanoSystem Institute	$100M/ 4 yrs
NY	Center of Excellence in Nanoelectronics; Albany Center	$50M, $400M/ 5 yrs
IL	Nanoscience Center (NU, U Ill, ANL)	$63M
PA	Nanotechnology Center	$37M
GA	Center at Georgia Tech	$25M
IN	Nanotechnology Center	$5M
TX	Nanotechnology Center	$0.5M over 2 yrs
SC	NanoCenter	$1M
AZ	Nanobio research	$5M for 20 years
NM	Consortium University of NM and National labs	
NJ	Support at NJIT and future nanophotonics consortium	
FL	Center at the University of South Florida	
OK	Nano-Net (~$3M/yr for 5 years)	

- OH (support Center $27M in Columbus), TN ($24M), Louisiana, CT, MA, VA, AZ

NNI challenges

- **Need for coherent, long-term (5-10 yrs) vision / programs**
- **Horizontal versus vertical S&T development:**
  0.7% (on fundamental research – to continue) versus 5% (plus precompetitive R&D) of US R&D budget
- **Competitiveness: Strengthening partnership w/ industry**

  Need for system-oriented programs, focused on topics such as: the new transistor, new display, new catalyst, conditioning the cell, S&T convergence

  Support: Joint R&D in university-industry networks and industry-government laboratories to facilitate new technologies and commercialization